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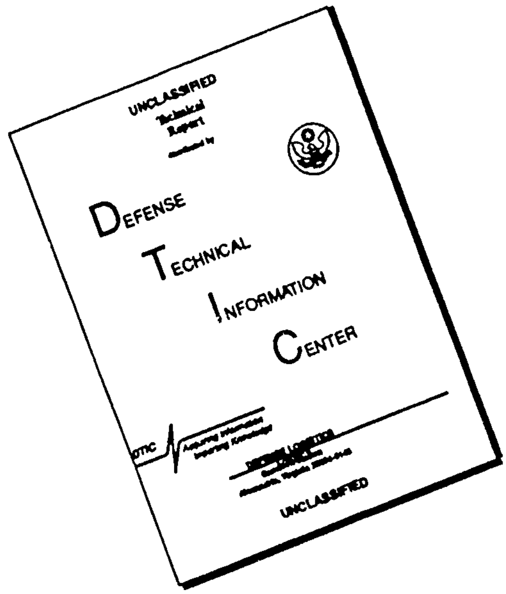

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CRDKNSWC-HD-0386-135 December 1993
Hydromechanics Directorate
Directorate Report

HYDRODYNAMIC TOWING STABILITY EVALUATION OF SSN-688 CLASS SUBMARINES

by

Mark S. Fellman

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An experimental evaluation was conducted to investigate the surface towing characteristics of SSN-688 class submarines. A 1/22.5-scale model was towed in the David Taylor Model Basin with variations in displacement, trim, metacentric height (GM), towpoint location and with several stern appendage modifications. The SSN-688 class submarine was towed in a stable configuration at speeds up to 10 kn with the sternplanes set to 25 deg trailing edge up, at a trim between 6.0 and 7.5 ft (1.83 and 2.29 m) down by the stern, at a displacement between 5000 and 5650 LTSW, with a GM between 0.75 and 1.10 ft (0.23 and 0.34 m), with the lower rudder extended 2.25 ft (0.69 m) and with a lower rudder plate appendage attached.

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ABSTRACT

An experimental evaluation was conducted to investigate the surface towing characteristics of SSN-688 class submarines. A 1/22.5-scale model was towed in the David Taylor Model Basin with variations in displacement, trim, metacentric height (GM), towpoint location and with several stern appendage modifications. The SSN-688 class submarine was towed in a stable configuration at speeds up to 10 kn with the sternplanes set to 2° deg trailing edge up, at a trim between 6.0 and 7.5 ft (1.83 and 2.29 m) down by the stern, at a displacement between 5000 and 5650 LTSW, with a GM between 0.75 and 1.10 ft (0.23 and 0.34 m), with the lower rudder extended 2.25 ft (0.69 m) and with a lower rudder plate appendage attached.

ADMINISTRATIVE INFORMATION

This project was sponsored by the Naval Sea Systems Command (NAVSEA) PMS 396 under Work Request N0002492PX01521 of 13 August 1992 with NAVSEA PMS 393 as the technical point of contact. This work was performed by the Towed and Special Systems Branch (Code 541) of the David Taylor Model Basin (DTMB), Carderock Division, Naval Surface Warfare Center (CARDEROCKDIV, NSWC) under Work Unit 1-1541-172.

INTRODUCTION

At the request of the Naval Sea Systems Command (NAVSEA), the David Taylor Model Basin, Carderock Division Headquarters, Naval Surface Warfare Center (CARDEROCKDIV, NSWC) undertook a program to investigate the surface towing characteristics of SSN-688 class submarines. Several SSN-688 class submarines are scheduled to be decommissioned and will need to be surface towed in transit from various shipyards to their designated storage sites. The submarines will need to be towed in a stable manner in the open ocean. Several basic evaluations have looked at stabilizing efforts for a submarine under tow[1,2].

This effort was undertaken to determine stable towing configurations for SSN-688 class submarines. The effects of towpoint location, trim, metacentric

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1 *Fellman, M.S. and Para, R.P., "Hydrodynamic Towing Evaluation of SSN-637 Class Short-hull and Long-hull Submarines with Modified Bows," DTRC Report SHD-0540-25 (May 1991).*

2 *Fellman, M.S. and Para, R.P., "Hydrodynamic Towing Evaluation of SSBN-640 Class Submarines," DTRC Report SHD-1365-01 (December 1991).*

height, sternplane aft extensions, sternplane tip plates, a lower-rudder plate, and an extended rudder with rudder plate, on towing stability were investigated. This report describes the model, experimental procedures and results. Average steady state horizontal towline angle and predicted average steady state full-scale towline tension are presented as a function of speed for various trim and ballast configurations with numerous stern appendages attached. A video documentary was prepared to illustrate the submarine towing stability procedure and was distributed with this report.

STABILITY CRITERIA

In the field of naval architecture, the longitudinal stability of a ship is defined by how well it will move in a straight line without turning. In towing applications, longitudinal stability can be described by two characteristics: Decay and Position.

Decay characterizes the rate at which a tow will reduce its outboard excursion behind the tug. The accepted definition of a stable tow is one that will decay at the rate of one half of its excursion amplitude per cycle. If the tow yaws and moves outboard a distance D_1 to starboard of the centerline of the tug on its first excursion, the next excursion D_2 to starboard will have to be equal to one half of D_1 to be considered stable, as illustrated in Fig. 1. Stability in decay is always a desirable quality of a tow and actions should be taken to ensure and improve the rate of its occurrence.

Position characterizes the location of the tow with respect to the tug. The classic description of a stable tow has the tow positioned directly astern of the tug. A tow that yaws and moves outboard less than ±15 deg to one side of the tug and stays at one position in repeated tests also is a positionally stable tow, although less desirable. Horizontal towline angles of less than 10 deg are preferred. Positional stability is illustrated in Fig. 2.

A tow can be characterized as unstable due to decay rate, wandering or position. If the decay rate is slower than defined above, the tow is considered unstable. Tow wandering, which is a random and varying positional instability, is illustrated in Fig. 3. Positional instability is characterized as a constant

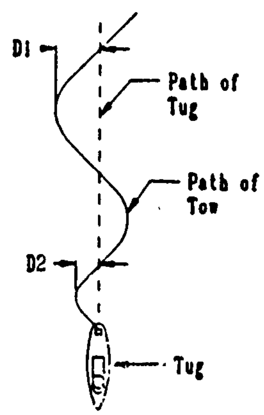

Fig. 1. Decay node stability.

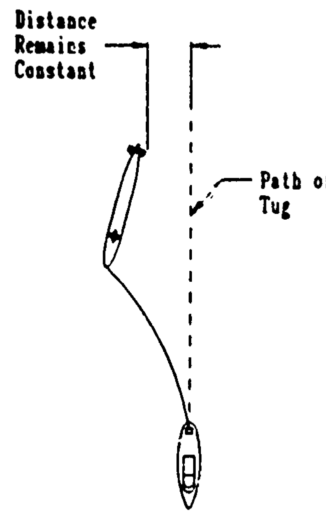

Fig. 2. Positional stability.

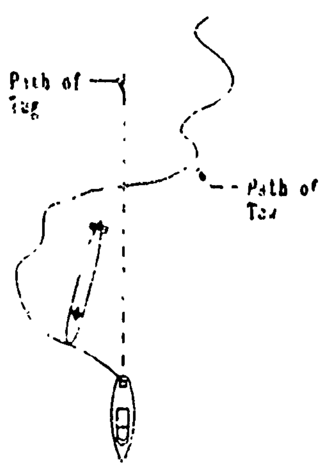

Fig. 3. Example of tow wandering.

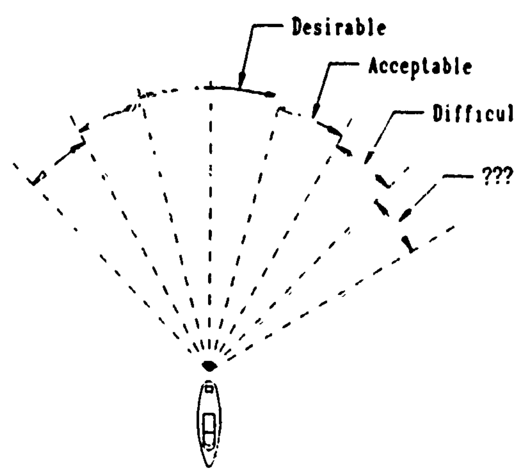

Fig. 4. Degrees of difficulty caused by wandering of the towed vessel.

horizontal towline angle larger than ±15 deg from a position directly astern of the tug.

Once the tow goes to sea, the success of the tow depends on a variety of factors such as sea conditions, tug horsepower, type of tow gear, tug configuration, experience of the tug crew and skipper, etc. For these reasons, it is difficult to put exact numbers on the towing stability. However, if the tow stays close to the centerline of the tug path, there will be little difficulty in handling it. If the tow yaws to an acceptable limit, with fast decay and positional stability, handling is possible with some loss of tow speed and increase in towline tension. As the tow yaws and moves further outboard from a centerline position behind the tug, the towline tension increases and tow speed must be significantly reduced. Furthermore, the tow would be dangerous to itself and other ships when in restricted waters, and the tug could be in danger of tripping; that is, rolling over due to side loading. The progression of tow instability is illustrated in Fig. 4.

MODEL DESCRIPTION

A 16.0 ft (4.88 m) long fiberglass model (DTMB #5361) was used for this basin evaluation. The model has a linear scale ratio (λ) of 22.5 which corresponds to a full-scale length of 360 ft (109.7 m). The propeller was removed for the evaluation. The moveable sternplanes were evaluated at a setting of 25 deg trailing edge up (TEU) for all configurations. The SSN-688 class was evaluated with removable towed array tubes/fairings attached to the tips of both fixed sternplanes as shown in Fig. 5. The equivalent full-scale ballast conditions are listed in Table 1 and the primary dimensions of the SSN-688 class are illustrated in Fig. 6.

Stern configurations evaluated for the SSN-688 class included moveable sternplane aft extensions, fixed sternplane tip plates, a 1/2 area Rudder Plate, and a 2.7 ft (0.82 m) extended lower rudder with a 1/2 area Rudder Plate. The area of one aft extension is equal to one half the area of the sternplane moveable flap and is shown in Fig. 7. The tip plates had a half span of 4.0 ft (1.22 m), a tip chord of 6.1 ft (1.86 m) and a centerline chord of 8.0 ft (2.44

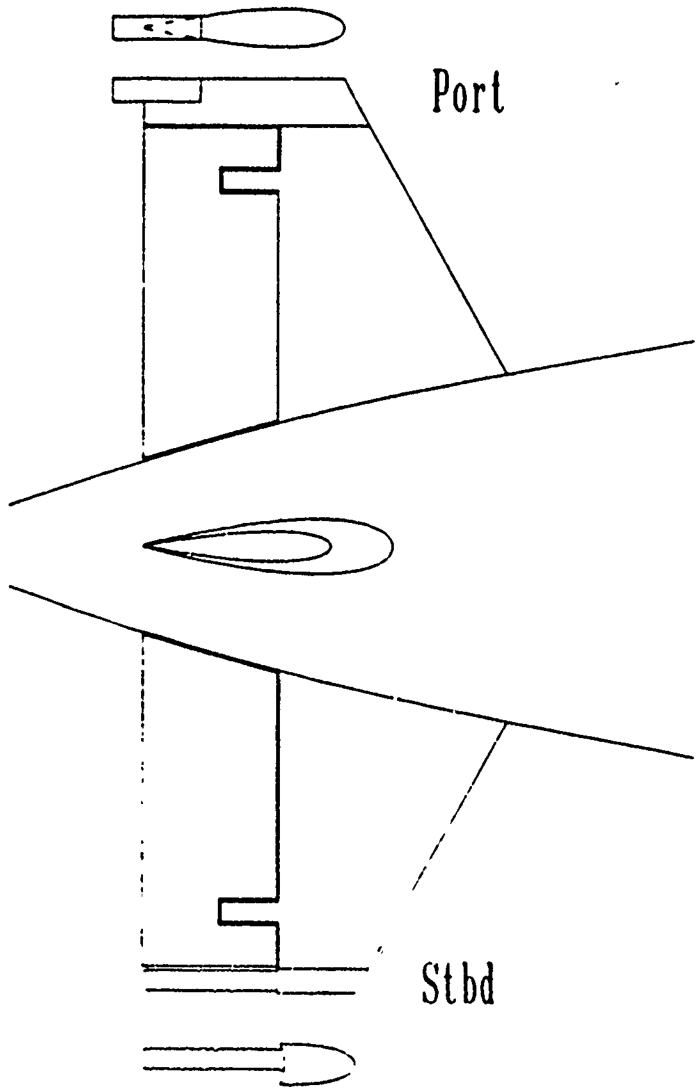

Fig. 5. General layout of port and starboard towed array tubes for SSN-688 class.

Table 1. Ballast conditions for SSN–688 class towing stability evaluation.

Waterline	Displacement LTSW (kg)	Trim FDM to ADM ft (m)	Trim FP to AP ft (m)	GM range ft (m)	Mean Draft ft (m)	FWD Draft Mark ft (m)	AFT Draft Mark ft (m)
1	5000 (5080235)	3.00 (0.91)	3.43 (1.05)	0.75 to 1.10 (0.23 to 0.34 m)	22.46 (6.85)	20.78 (6.33)	23.77 (7.25)
2	5000 (5080235)	4.50 (1.37)	5.14 (1.57)	0.75 to 1.10 (0.23 to 0.34 m)	22.46 (6.85)	20.15 (6.14)	24.65 (7.51)
3	5000 (5080235)	6.00 (1.83)	6.86 (2.09)	0.75 to 1.10 (0.23 to 0.34 m)	22.46 (6.85)	19.52 (5.95)	25.52 (7.78)
4	5000 (5080235)	7.50 (2.29)	8.57 (2.61)	0.75 to 1.10 (0.23 to 0.34 m)	22.46 (6.85)	18.90 (5.76)	26.40 (8.05)
5	5650 (5740666)	3.00 (0.91)	3.43 (1.05)	0.75 to 1.10 (0.23 to 0.34 m)	25.12 (7.66)	23.38 (7.13)	26.38 (8.04)
6	5650 (5740666)	4.50 (1.37)	5.14 (1.57)	0.75 to 1.10 (0.23 to 0.34 m)	25.12 (7.66)	22.78 (6.94)	27.28 (8.31)
7	5650 (5740666)	6.00 (1.83)	6.86 (2.09)	0.75 to 1.10 (0.23 to 0.34 m)	25.12 (7.66)	22.18 (6.76)	28.18 (8.59)
8	5650 (5740666)	7.50 (2.29)	8.57 (2.61)	0.75 to 1.10 (0.23 to 0.34 m)	25.12 (7.66)	21.59 (6.58)	29.09 (8.87)

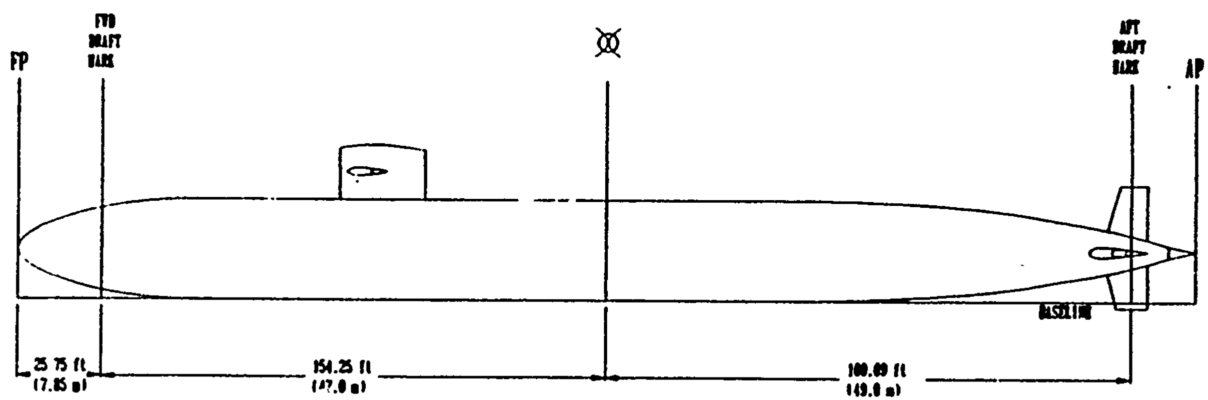

Fig. 6. SSN-688 Class primary dimensions.

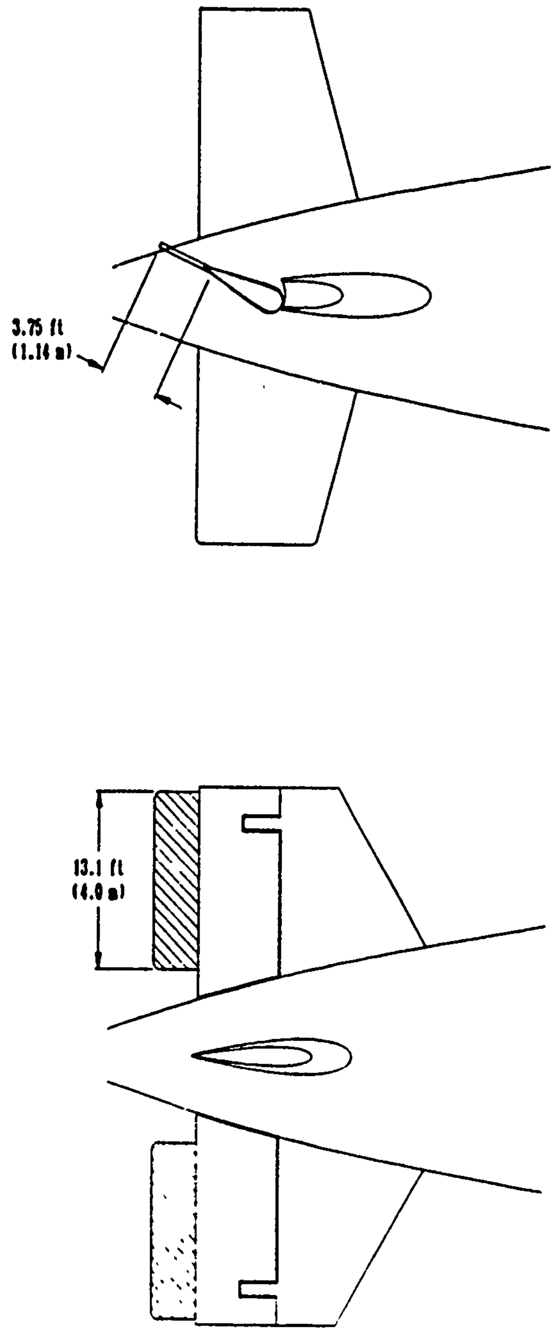

Fig. 7. Illustration of Aft Extensions on SSN-688 Class moveable sternplane flaps.

m) as shown in Fig. 8. The original lower rudder with 1/2 area Rudder Plate attached is shown in Fig. 9. In an attempt to make the 1/2 area Rudder Plate more effective, the lower rudder of SSN-688 was extended by 2.25 ft (0.69 m) using a flat plate parallel to the center chord of the rudder cross section, and the rudder plate was installed in a lower position. The extended lower rudder with 1/2 area Rudder Plate attached is shown in Fig. 10. Both rudder plates were installed at an angle of 25 deg trailing edge up (TEU) and had an area equal to 50 percent of the area of one moveable sternplane flap on each side of the lower rudder.

Two towpoint locations were evaluated for the SSN-688 class. Current plans for towing SSN-688 class submarines call for the use of a portable (removable) towing fixture similar to what is currently used to tow SSN-637 class submarines. The portable towing fixture surrounds the composite bow dome and attaches to pads welded to the outer hull as illustrated in Fig. 11. The tow fixture places the towpoints near the forward perpendicular which increases towing stability.

The Primary and Secondary towpoints were located 2.0 ft (0.61 m) forward of the forward perpendicular, on the centerline and 2.0 ft (0.61 m) above the centerline, respectively. These towpoint positions assume that the portable towing fixture proposed by Mare Island Naval Shipyard is used[3]. A future evaluation will determine if a stable tow can be achieved for SSN-688 class submarines with the bow dome removed so that the domes can be reused. For this future evaluation, a towpoint directly on the sonar sphere structure will be evaluated with or with out fairing plates.

The Primary model towline was a 15.0 ft (4.57 m) length of 1/8-inch (3.18 mm) diameter braided nylon line which represents a full-scale length of 337.5 ft (102.9 m). The Secondary model towline was a 40.0 ft (12.19 m) length of 1/32-in. (0.79 mm) wire rope which represents a full-scale length of 900.0 ft (274 m).

PROCEDURES

The model was statically trimmed for surface towing by ballasting to full-

[3] *NAVSHIPYD MARE letter Ser 250/3 of 23 Feb 93, "Design Estimate for SSN-588 Class Tow Bridle."*

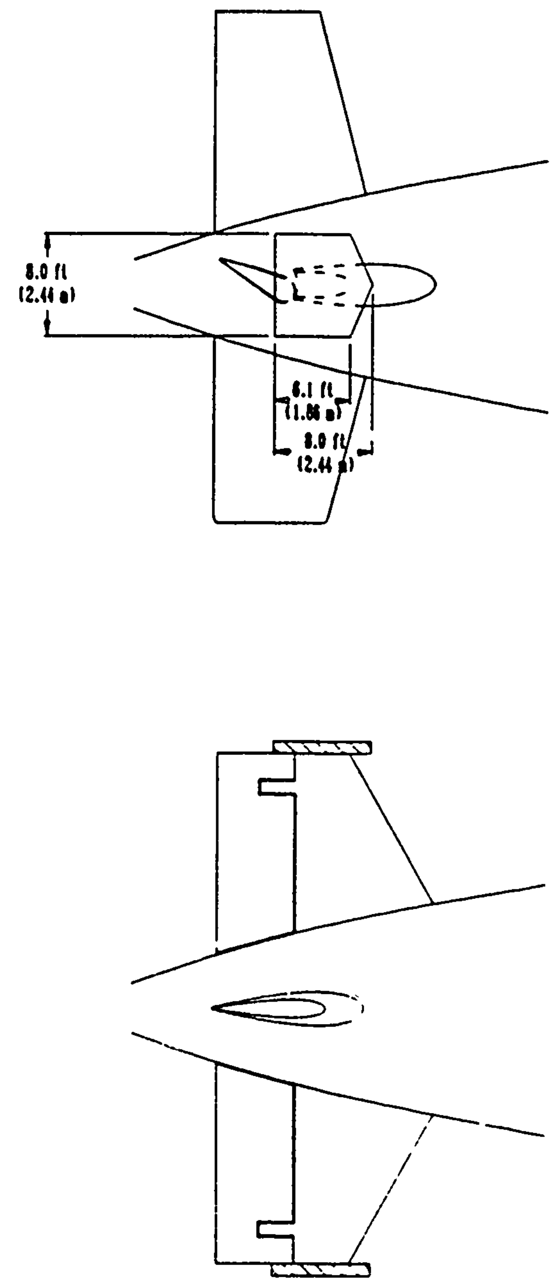

Fig. 8. Illustration of Tip Plates on SSN-688 Class fixed sternplanes.

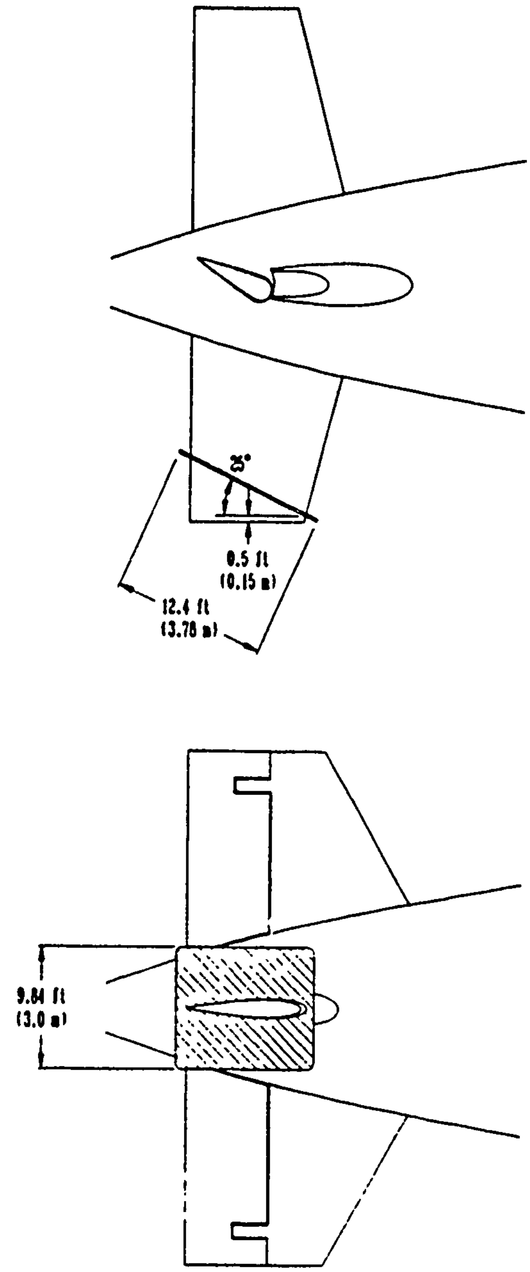

Fig. 9. Illustration of 1/2 Area Rudder Plate attached to existing SSN-688 Class lower rudder.

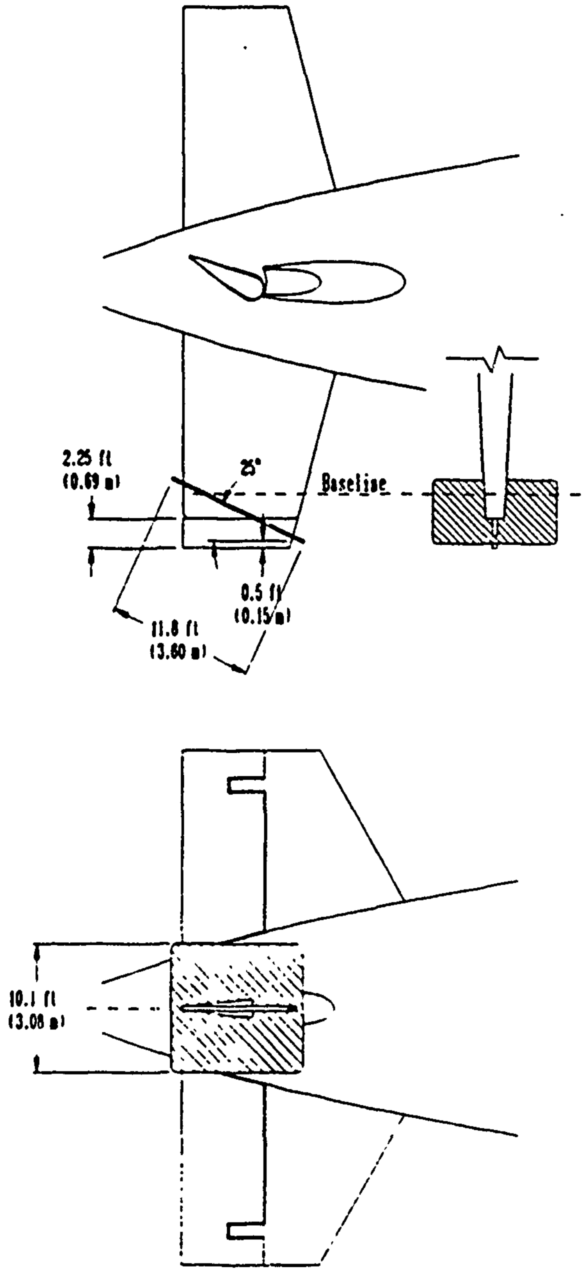

Fig. 10. Illustration of 1/2 Area Rudder Plate attached to the SSN-688 Class lower rudder with a 2.25 ft (0.69 m) rudder extension.

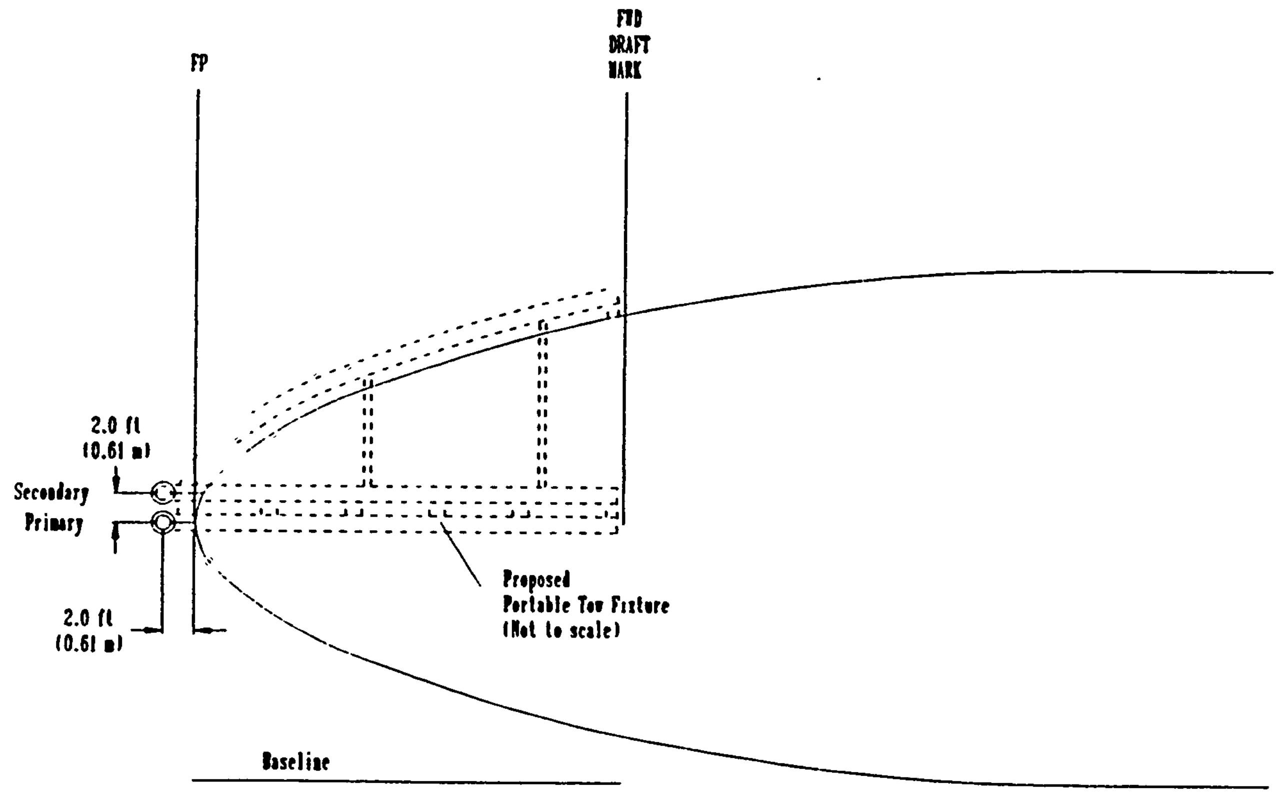

Fig. 11. Towpoint locations for SSN-688 Class towing stability evaluation.

scale displacements of 5000 and 5650 long tons sea water (LTSW) (5080235 and 5740666 kg). These displacements represent full-scale mean drafts of approximately 22.46 and 25.12 ft (6.85 and 7.66 m), respectively. Each displacement was ballasted for full-scale trims (between draft marks) of 3.0, 4.5, 6.0 and 7.5 ft (0.91, 1.37, 1.83 and 2.29 m) down by the stern, for a total of 8 waterlines. Roll incline tests were conducted to obtain the required full-scale metacentric heights (GM) of 0.75 and 1.10 ft (0.23 and 0.34 m) at each waterline.

The Primary towline and towpoint were used for most of the testing. The longer Secondary towline was evaluated for repeat runs of a single model configuration. Repeat runs with the Secondary towpoint were conducted for several stable model configurations at each tow speed. The sternplane array tubes were attached for most runs and were removed for repeat runs at several stable towing configurations to determine their effect on towing stability. Several runs were made with the lower rudder intentionally deflected to small angles to determine the effect on towing stability and equilibrium horizontal towline angle.

The towing evaluation was performed in the deep-water towing basin at DTMB. The basin is 22 ft (6.7 m) deep, 51 ft (15.5 m) wide and has an approximate run length of 1200 ft (365.8 m). The model was towed at the equivalent full-scale speeds of 4, 7 and 10 kn.

Once the towing carriage reached the desired speed, the model was displaced to one side of the tow carriage centerline and then was allowed to seek its equilibrium position. The towing stability was evaluated for stern configurations with and without aft extensions, tip plates and rudder plates at each waterline as required to stabilize the tow. Ballast conditions and stern modifications which were found unstable were not repeated at both displacements.

INSTRUMENTATION

The instrumentation located at the gimbal towpoint consisted of an angle potentiometer and a tension dynamometer. The gimbal was mounted to a bracket under the towing carriage approximately 14 in. (356 mm) above the water surface.

The angle potentiometer measured the horizontal towline angle, defined as the angle of the towline relative to the direction of tow, projected onto a horizontal plane. The potentiometer has a range of 60 deg port and starboard with a system accuracy of ±0.5 deg.

A 50-pound (222 N) capacity ring-gage tension dynamometer measured the towing tension with a system accuracy of ±0.15 lb (0.7 N). The full-scale accuracy would be equivalent to ±1,800 lb (7,800 N).

Additional instrumentation consisted of a magnetic pickup on the towing carriage to provide measurements of speed with a model accuracy of ±0.01 kn and a full-scale accuracy of ±0.05 kn. For all measurements, data were collected on an eight-channel stripchart recorder and digitally on a 486/33 MHz computer.

RESULTS AND DISCUSSIONS

All test results are presented as full-scale values. Froude scaling methods were used. All lengths were scaled by λ and towline tension was scaled by:

$$\frac{\rho_{sea}}{\rho_{fresh}} \cdot \lambda^3$$

where,

ρ_{sea} is the density of sea water at 59 deg F.
ρ_{fresh} is the density of fresh water at 68 deg F., and
λ is the linear scale ratio.

The stability criteria outlined above must be achieved at both displacements and both GMs for a given trim down by the stern to be considered a stable configuration. The testing sequence was selected to maximize the number of runs during the week long evaluation and was not necessarily conducted in the order presented. If the stability criteria were not achieved (and not marginal) at the first displacement evaluated, the other displacement was usually not evaluated for the same model configuration at the same trim.

The equilibrium horizontal towline angle measurements for the SSN-688 class submarine with various stern appendage modifications are presented as a function of speed in Tables 2 through 7 for the 5000 LTSW displacement and Tables 8 through 15 for the 5650 LTSW displacement. Only 11 of the 16 ballast conditions were tested because some unstable model configurations were not evaluated at both

Table 2. Horizontal towline angles for SSN–688 class submarine with a displacement of 5000 LTSW, a trim of 4.50 ft (1.37 m) down by the stern, and a GM of 0.75 ft (0.23 m).

Speed kn (m/s)	Horizontal Towline Angle, deg				
	Stern Configuration with Sternplane Angle, deg				
	No Extensions	Tip Plates	Aft Extensions	1/2 Area Rudder Plate	Ext. Rudder & 1/2 Area Rudder Plate
	25 TEU	25 TEU	25 TEU	25 TEU	25 TEU
4 (2.06)	34° P				19° P
7 (3.60)	38° P				19° P
10 (5.14)					

P – Port S – Starboard

Table 3. Horizontal towline angles for SSN–688 class submarine with a displacement of 5000 LTSW, a trim of 4.50 ft (1.37 m) down by the stern, and a GM of 1.1 ft (0.34 m).

Speed kn (m/s)	Horizontal Towline Angle, deg				
	Stern Configuration with Sternplane Angle, deg				
	No Extensions	Tip Plates	Aft Extensions	1/2 Area Rudder Plate	Ext. Rudder & 1/2 Area Rudder Plate
	25 TEU	25 TEU	25 TEU	25 TEU	25 TEU
4 (2.06)					
7 (3.60)	NO DATA COLLECTED FOR THIS CONFIGURATION				
10 (5.14)					

P – Port S – Starboard

Table 4. Horizontal towline angles for SSN–688 class submarine with a displacement of 5000 LTSW, a trim of 6.00 ft (1.83 m) down by the stern, and a GM of 0.75 ft (0.23 m).

Speed kn (m/s)	Horizontal Towline Angle, deg				
	Stern Configuration with Sternplane Angle, deg				
	No Extensions 25 TEU	Tip Plates 25 TEU	Aft Extensions 25 TEU	1/2 Area Rudder Plate 25 TEU	Ext. Rudder & 1/2 Area Rudder Plate 25 TEU
4 (2.06)	23° P	18° P	26° P	13° P	11° P
7 (3.60)	27° P	17° P increasing	23° P wandering ±3°	15° P wandering ±2°	8° P steady
10 (5.14)	4° P wandering ±4°			±3° wandering	1° P steady

P – Port S – Starboard

Table 5. Horizontal towline angles for SSN–688 class submarine with a displacement of 5000 LTSW, a trim of 6.00 ft (1.83 m) down by the stern, and a GM of 1.1 ft (0.34 m).

Speed kn (m/s)	Horizontal Towline Angle, deg				
	Stern Configuration with Sternplane Angle, deg				
	No Extensions 25 TEU	Tip Plates 25 TEU	Aft Extensions 25 TEU	1/2 Area Rudder Plate 25 TEU	Ext. Rudder & 1/2 Area Rudder Plate 25 TEU
4 (2.06)				14° P	10° P
7 (3.60)				15° P wandering ±3°	10° P steady
10 (5.14)				±2° wandering	1° P steady

P – Port S – Starboard

Table 6. Horizontal towline angles for SSN–688 class submarine with a displacement of 5000 LTSW, a trim of 7.50 ft (2.29 m) down by the stern, and a GM of 0.75 ft (0.23 m).

Speed kn (m/s)	Horizontal Towline Angle, deg				
	Stern Configuration with Sternplane Angle, deg				
	No Extensions 25 TEU	Tip Plates 25 TEU	Aft Extensions 25 TEU	1/2 Area Rudder Plate 25 TEU	Ext. Rudder & 1/2 Area Rudder Plate 25 TEU
4 (2.06)	10–12° P increasing	11° P		6° P wandering ±2°	6° P steady
7 (3.60)	13–17° P increasing	13° P		7° P wandering ±2°	5° P steady
10 (5.14)	±4° wandering	0°		1° S wandering ±2°	1° S

P – Port S – Starboard

Table 7. Horizontal towline angles for SSN–688 class submarine with a displacement of 5000 LTSW, a trim of 7.5 ft (2.29 m) down by the stern, and a GM of 1.1 ft (0.34 m).

Speed kn (m/s)	Horizontal Towline Angle, deg				
	Stern Configuration with Sternplane Angle deg				
	No Extensions 25 TEU	Tip Plates 25 TEU	Aft Extensions 25 TEU	1/2 Area Rudder Plate 25 TEU	Ext. Rudder & 1/2 Area Rudder Plate 25 TEU
4 (2.06)		7° P wandering ±7°		6° P steady	6° P steady
7 (3.60)		6° P wandering ±1°		8° P	6° P steady
10 (5.14)		1° S steady		2° S wandering ±2°	1° S wandering ±2°

P – Port S – Starboard

Table 8. Horizontal towline angles for SSN–688 class submarine with a displacement of 5650 LTSW, a trim of 3.00 ft (0.91 m) down by the stern, and a GM of 0.75 ft (0.23 m).

Speed kn (m/s)	Horizontal Towline Angle, deg — Stern Configuration with Sternplane Angle, deg: No Extensions 25 TEU	Tip Plates 25 TEU	Aft Extensions 25 TEU	1/2 Area Rudder Plate 25 TEU	Ext. Rudder & 1/2 Area Rudder Plate 25 TEU
4 (2.06)	35° P				22° P wandering ±4°
7 (3.60)	33° P wandering ±3°				8° P wandering ±6°
10 (5.14)	7° P wandering ±7°				4° P

P – Port S – Starboard

Table 9. Horizontal towline angles for SSN–688 class submarine with a displacement of 5650 LTSW, a trim of 3.00 ft (0.91 m) down by the stern, and a GM of 1.1 ft (0.34 m).

Speed kn (m/s)	Horizontal Towline Angle, deg — Stern Configuration with Sternplane Angle, deg: No Extensions 25 TEU	Tip Plates 25 TEU	Aft Extensions 25 TEU	1/2 Area Rudder Plate 25 TEU	Ext. Rudder & 1/2 Area Rudder Plate 25 TEU
4 (2.06)					
7 (3.60)	NO DATA COLLECTED FOR THIS CONFIGURATION				
10 (5.14)					

P – Port S – Starboard

Table 10. Horizontal towline angles for SSN–688 class submarine with a displacement of 5650 LTSW, a trim of 4.50 ft (1.37 m) down by the stern, and a GM of 0.75 ft (0.23 m).

Speed kn (m/s)	Horizontal Towline Angle, deg				
	Stern Configuration with Sternplane Angle, deg				
	No Extensions 25 TEU	Tip Plates 25 TEU	Aft Extensions 25 TEU	1/2 Area Rudder Plate 25 TEU	Ext. Rudder & 1/2 Area Rudder Plate 25 TEU
4 (2.06)	7–15° P wandering				11° P wandering ±3°
7 (3.60)	5° P – 6° S wandering				7° P wandering ±2°
10 (5.14)	3° P – 5° S wandering				2° P wandering ±2°

P – Port S – Starboard

Table 11. Horizontal towline angles for SSN–688 class submarine with a displacement of 5650 LTSW, a trim of 4.50 ft (1.37 m) down by the stern, and a GM of 1.1 ft (0.34 m).

Speed kn (m/s)	Horizontal Towline Angle, deg				
	Stern Configuration with Sternplane Angle, deg				
	No Extensions 25 TEU	Tip Plates 25 TEU	Aft Extensions 25 TEU	1/2 Area Rudder Plate 25 TEU	Ext. Rudder & 1/2 Area Rudder Plate 25 TEU
4 (2.06)					
7 (3.60)	NO DATA COLLECTED FOR THIS CONFIGURATION				
10 (5.14)					

P – Port S – Starboard

Table 12. Horizontal towline angles for SSN–688 class submarine with a displacement of 5650 LTSW, a trim of 6.00 ft (1.83 m) down by the stern, and a GM of 0.75 ft (0.23 m).

Speed kn (m/s)	Horizontal Towline Angle, deg				
	Stern Configuration with Sternplane Angle, deg				
	No Extensions 25 TEU	Tip Plates 25 TEU	Aft Extensions 25 TEU	1/2 Area Rudder Plate 25 TEU	Ext. Rudder & 1/2 Area Rudder Plate 25 TEU
4 (2.06)	3° – 9° P wandering			2° P wandering ±2°	4° P wandering ±2°
7 (3.60)	2° S wandering ±2°			3° P – 3° S wandering	1° P steady
10 (5.14)	4° S wandering ±2°			10° S wandering ±3°	1° P steady

P – Port S – Starboard

Table 13. Horizontal towline angles for SSN–688 class submarine with a displacement of 5650 LTSW, a trim of 6.00 ft (1.83 m) down by the stern, and a GM of 1.1 ft (0.34 m).

Speed kn (m/s)	Horizontal Towline Angle, deg				
	Stern Configuration with Sternplane Angle, deg				
	No Extensions 25 TEU	Tip Plates 25 TEU	Aft Extensions 25 TEU	1/2 Area Rudder Plate 25 TEU	Ext. Rudder & 1/2 Area Rudder Plate 25 TEU
4 (2.06)				4° P wandering ±3°	3° P wandering ±2°
7 (3.60)				1° S wandering ±2°	1° S steady
10 (5.14)				3° S wandering ±2°	4° S wandering ±2°

P – Port S – Starboard

Table 14. Horizontal towline angles for SSN–688 class submarine with a displacement of 5650 LTSW, a trim of 7.50 ft (2.29 m) down by the stern, and a GM of 0.75 ft (0.23 m).

Speed kn (m/s)	Horizontal Towline Angle, deg				
	Stern Configuration with Sternplane Angle, deg				
	No Extensions 25 TEU	Tip Plates 25 TEU	Aft Extensions 25 TEU	1/2 Area Rudder Plate 25 TEU	Ext. Rudder & 1/2 Area Rudder Plate 25 TEU
4 (2.06)	4° P – 1° S wandering	1° P steady		0°	3° P steady
7 (3.60)	5° P – 1° S wandering	3° P steady		2° P wandering ±2°	3° P steady
10 (5.14)	2° P – 4° S wandering	2° – 13° S wandering		2° – 7° S wandering	4° P – 3° S wandering

P – Port S – Starboard

Table 15. Horizontal towline angles for SSN–688 class submarine with a displacement of 5650 LTSW, a trim of 7.5 ft (2.29 m) down by the stern, and a GM of 1.1 ft (0.34 m).

Speed kn (m/s)	Horizontal Towline Angle, deg				
	Stern Configuration with Sternplane Angle, deg				
	No Extensions 25 TEU	Tip Plates 25 TEU	Aft Extensions 25 TEU	1/2 Area Rudder Plate 25 TEU	Ext. Rudder & 1/2 Area Rudder Plate 25 TEU
4 (2.06)		0°		1° P wandering ±2°	1° P steady
7 (3.60)		1° P – 2° S wandering		2° P	1.5° P
10 (5.14)		6° S wandering ±3°		6° – 13° S wandering	5° P wandering ±2°

P – Port S – Starboard

GMs as indicated. The unstable 3.0 ft (0.91 m) trim condition was not evaluated at the 5000 LTSW displacement. The tables include notation concerning tow wandering where "steady" indicates less than ±1° of wandering and no comment indicates less than ±2° of wandering.

With a 5000 LTSW displacement, a 0.75 ft (0.23 m) GM and a 4.5 ft (1.37 m) trim down by the stern, SSN-688 was unstable in the baseline configuration (No extensions) with horizontal towline angles larger than 30 deg as shown in Table 2. Adding the extended lower rudder and rudder plate at this trim reduced the towline angle to approximately 20 deg. The other extensions were found to be less beneficial and were not evaluated at this trim. No data were collected at the 1.10 ft (0.34 m) GM at this trim since there were no stable configurations.

Increasing the trim from 4.5 ft (1.37 m) to 6.0 ft (1.83 m) down by the stern with a 0.75 ft (0.23 m) GM at the 5000 LTSW displacement reduced the measured horizontal towline angles as shown in Table 4. Changing the GM to 1.10 ft (0.34 m) had little effect at the 6.0 ft (1.37 m) trim and the data for this configuration are presented in Table 5. SSN-688 was still unstable in the baseline configuration with horizontal towline angles near 25 deg. Adding the aft extensions to the moveable sternplanes had a negligible effect on horizontal towline angle. The tip plates reduced the horizontal towline angle by approximately 5 to 10 deg when added to the baseline configuration, but the resulting angles were still considered unstable. The rudder plate on the original rudder produced a marginally stable tow with a maximum horizontal towline angle of 15 deg with ±2 deg of wandering at 7 kn. Steady horizontal towline angles of 11, 8 and 1 deg were achieved with the extended lower rudder and rudder plate at 4, 7 and 10 kn, respectively.

A stable tow was achieved for SSN-688 at a 7.5 ft (2.29 m) trim down by the stern with either GM at the 5000 LTSW displacement with the rudder plate attached to either the original rudder or the extended rudder as shown in Tables 6 and 7. Again, the ±2 deg towline wandering was reduced when the rudder plate was in the lower position with the extended rudder. For both locations of the rudder plate, horizontal towline angles were less than 10 deg for the speed range of 4 to 10 kn at either GM. The tip plates produced towline angles of less than 15 deg at

the 7.5 ft (2.29 m) trim, however excessive wandering of up to ±7 deg at 4 kn caused this modification to be classified as unstable. For tip plates to be effective, they must be exposed to an angle of attack with the flow so that they provide a restoring moment to correct the submarine yaw. At slow speeds, an oscillating horizontal towline angle may be the result of overcompensation due to inertial effects once the submarine yaw angle is changing. As speed was increased to 10 kn, no horizontal towline angle oscillation was evident with the tip plates and steady state angles were near 0 deg. The tip plates might be more effective at slow speeds if they were splayed with respect to the submarine centerline.

Submarines under tow have been found to be generally more stable for a given sternplane configuration when displacement is increased. For this reason, the 3.0 ft (0.91 m) trim down by the stern was only evaluated on SSN-688 at the 5650 LTSW displacement as shown in Table 8. In the baseline configuration (no extensions) at the large displacement and 3.0 ft (0.91 m) trim, horizontal towline angles were over 30 deg with excessive wandering. Adding the extended lower rudder and rudder plate reduced the angle by more than 10 deg but increased the magnitude of wandering at this trim. At the large displacement and small trim down by the stern, the bow is deeper in the water and the hydrodynamic forces on the bow have a destabilizing effect. No data were collected at the 1.10 ft (0.34 m) GM since the 0.75 ft (0.23 m) GM proved unstable.

Increasing the trim from 3.0 ft (0.91 m) to 4.5 ft (1.37 m) with a 0.75 ft (0.23 m) GM at the 5650 LTSW displacement significantly reduced the horizontal towline angles for the baseline configuration as shown in Table 10. However, excessive wandering was still present. Adding the rudder plate and extended rudder at the 4.5 ft (1.37 m) trim did not reduce the horizontal towline angles significantly, but did reduce the magnitude of wandering. No data were collected at the 1.10 ft (0.34 m) GM since the 0.75 ft (0.23 m) GM proved unstable.

Several stable configurations were identified with a 6.0 ft (1.83 m) trim down by the stern at the 5650 LTSW displacement as shown in Tables 12 and 13. The horizontal towline angles for the baseline configuration at the 0.75 ft (0.23 m) GM were less than 10 deg with wandering of up to ±3 deg. Adding the rudder

plate to the original rudder reduced the towline angle and wandering slightly at 4 and 7 kn, but not at 10 kn. With the extended lower rudder and rudder plate, a stable tow was achieved with horizontal towline angles of less than 5 deg for both GMs at the 6.0 ft (1.83 m) trim.

At the 7.5 ft (2.29 m) trim and 5650 LTSW displacement, SSN-688 had horizontal towline angles of less than 10 deg but generally exhibited ±3 deg of wandering in the baseline configuration as shown in Tables 14 and 15. The tip plates provided horizontal towline angles of less than 5 deg at 4 and 7 kn, but displayed tendencies to wander to larger horizontal towline angles at 10 kn. Adding the rudder plate to either the original or extended lower rudder kept horizontal towline angles below 5 deg at 4 and 7 kn, but ±3 deg of wandering was still present at 10 kn. The tow tended to be more positionally stable with the extended lower rudder. No predictable differences were observed between the 0.75 and 1.10 ft (0.23 and 0.34 m) GMs.

For all conditions evaluated, moving the towpoint location from the Primary position (on the centerline, 2 ft forward of the forward perpendicular) to the Secondary position (2 ft above the Primary position) did not have a significant effect on average steady state horizontal towline angle or towing tension at speeds up to 10 kn. Fluctuations in horizontal towline angle between the 0.75 and 1.10 ft (0.23 and 0.34 m) GM for a fixed model configuration were inconsistent and generally less than 2 deg in all cases. The SSN-688 class was slightly more stable at the heavier (5650 LTSW) displacement.

A comparison of the horizontal towline angles for SSN-688 with various stern modifications evaluated at a 5000 LTSW displacement and 6.0 ft (1.83 m) trim down by the stern at 4 and 7 kn are presented in Figs. 12 and 13, respectively. It is evident that a positionally stable tow is not achieved until the rudder plate is moved lower using the extended rudder at the 6.0 ft (1.83 m) trim down by the stern.

The horizontal towline angles for SSN-688 with a 5000 LTSW displacement and 7.5 ft (2.29 m) trim down by the stern at 4 and 7 kn are presented in Figs. 14 and 15, respectively. All configurations were more stable when the trim was increased from 6.0 to 7.5 ft (1.83 to 2.29 m) down by the stern. A very stable

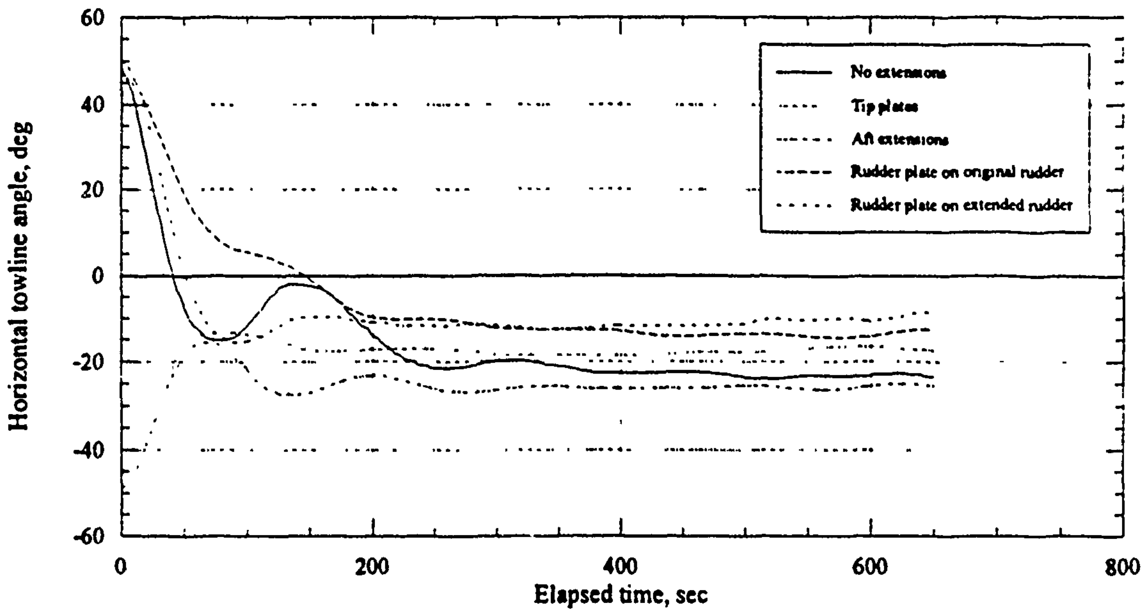

Fig. 12. Effect of stern appendages on SSN-688 class at 5000 LTSW displacement, 0.75 ft (0.23 m) GM and 6.0 ft (1.82 m) trim down by the stern at 4 kn.

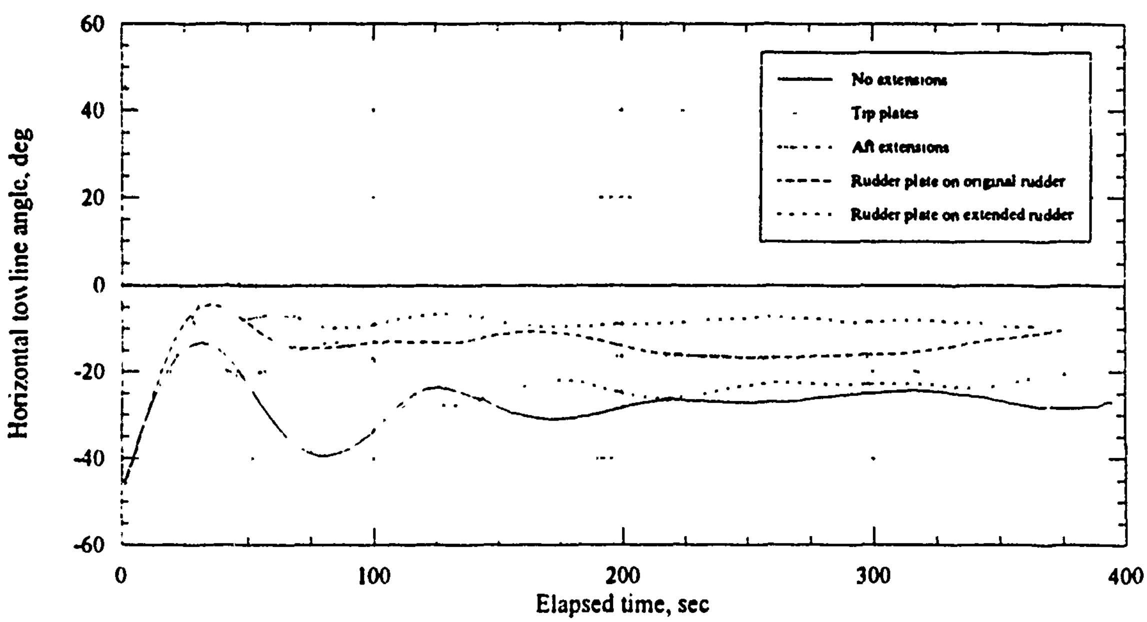

Fig 13 Effect of stern appendages on SSN-688 class at 5000 LTSW displacement, 0.75 ft (0.23 m) GM, and 6 0 ft (1.83 m) trim down by the stern at 7 kn.

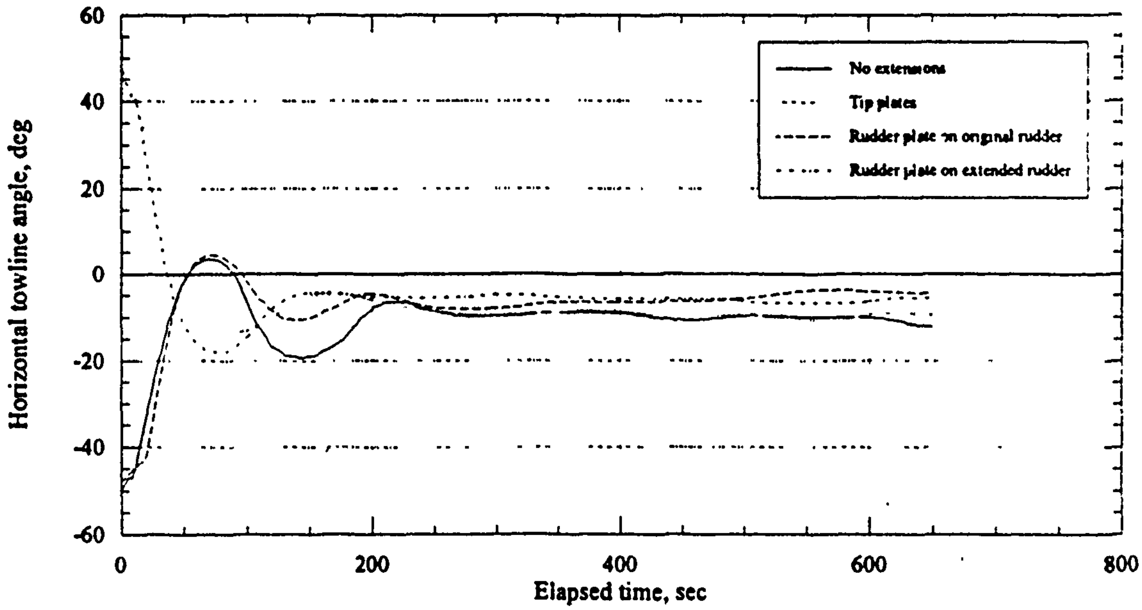

Fig. 14. Effect of stern appendages on SSN-688 class at 5000 LTSW displacement, 0.75 ft (0.23 m) GM and 7.5 ft (2.29 m) trim down by the stern at 4 kn.

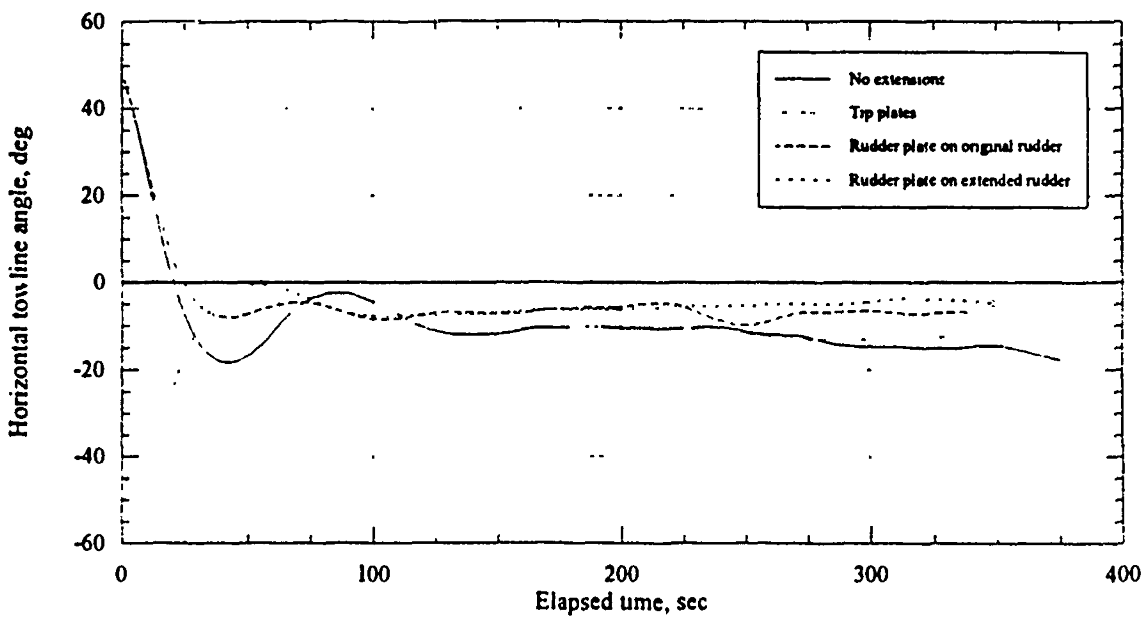

Fig. 15. Effect of stern appendages on SSN-688 class at 5000 LTSW displacement, 0.75 ft (0.23 m) GM, and 7.5 ft (2.29 m) trim down by the stern at 7 kn

tow was achieved with the rudder plate on either the original or the extended rudder. However, less wandering and a slightly smaller angle occurred with the extended rudder position. The tip plates provided a positionally stable tow at the 7.5 ft (2.29 m) trim, but at larger horizontal towline angles than with the rudder plate.

Previous submarine towing evaluations have shown that increasing the trim down by the stern increases the towing stability. The effect of trim on SSN-688 with an extended lower rudder and rudder plate is shown in Fig. 16. Increasing the trim down by the stern increased towing stability significantly.

The sternplane array tubes/fairings were removed for repeat runs on all stable towing configurations. As shown in Fig. 17 for runs at both 4 and 7 kn, the effect of the array tubes on towing stability was considered negligible for the indicated configuration and all other configurations evaluated.

Most of the evaluation was conducted using the 337.5 ft (102.9 m) long Primary towline. Repeat runs with the 900.0 ft (274.3) m) long Secondary towline had steady state horizontal towline angles that were the same to within the accuracy of the measurement (±0.5 deg) as shown in Fig. 18 and 19 for speed of 4 and 7 kn, respectively. The hypothesis that towline length does not affect the towing behavior of the model has been confirmed during several previous surface towing evaluations at DTMB[4]. Figure 19 also includes two runs, with and without array tubes, which have nearly identical initial perturbations and subsequent reactions.

Near the end of the evaluation, a series of runs was made to determine the effect of the lower rudder setting on the equilibrium horizontal towline angle. The SSN-688 was ballasted to its most stable condition with a 5650 LTS^{W} displacement, a 7.5 ft (2.29 m) trim down by the stern and with the extended lower rudder and rudder plate attached. The lower rudder was set to deflections of 1 and 2 deg port and starboard and the resulting horizontal towline angles are presented in Table 16. The results indicate that a small rudder deflection can increase the towline angle by 10 deg at tow speeds of 4 and 7 kn and can initiate

[4] *Fellman, Mark S. "Synthetic Spring Tow Hawser Model Experiments in a Seaway," CARDEROCKDIV SHD-1390-01, June 1992.*

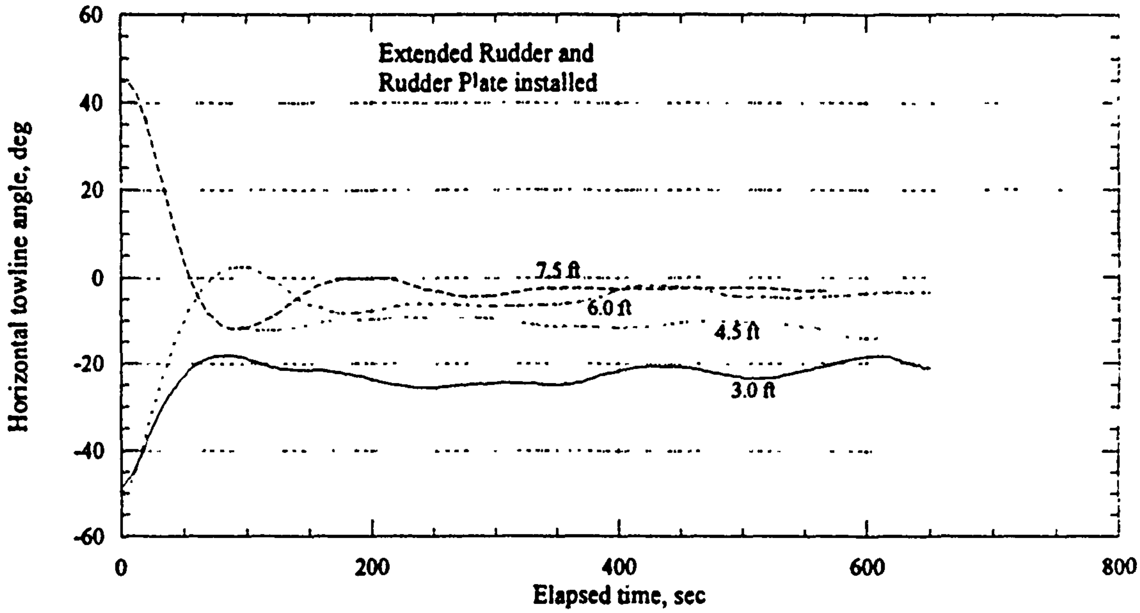

Fig. 16. Effect of trim down by the stern on SSN-688 class at 5650 LTSW displacement, 0.75 ft (0.23 m) GM and with an extended lower rudder and rudder plate at 4 kn.

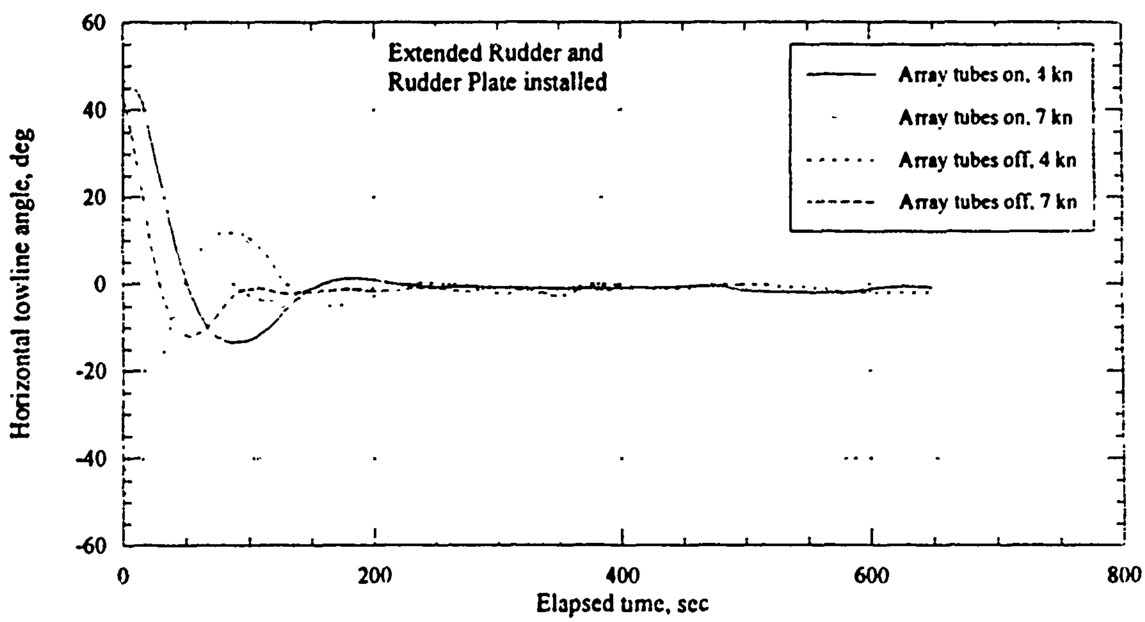

Fig 17 Effect of towed array tubes on SSN-688 class at 5650 LTSW, 1 1 ft (0.34 m) GM, 7 5 ft (0.229 m) trim down by the stern and with an extended lower rudder and rudder plate at 4 and 7 kn

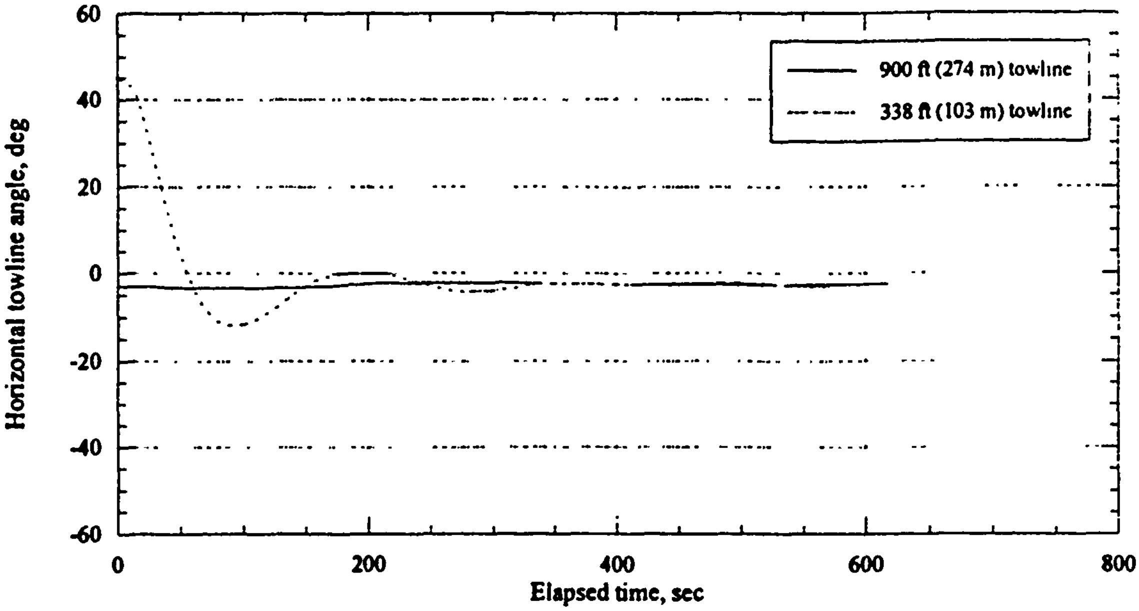

Fig. 18. Effect of towline length on SSN-688 class at 5650 LTSW displacement, 0.75 ft (0.23 m) GM, 7.5 ft (2.29 m) trim down by the stern, and with an extended lower rudder and rudder plate at 4 kn

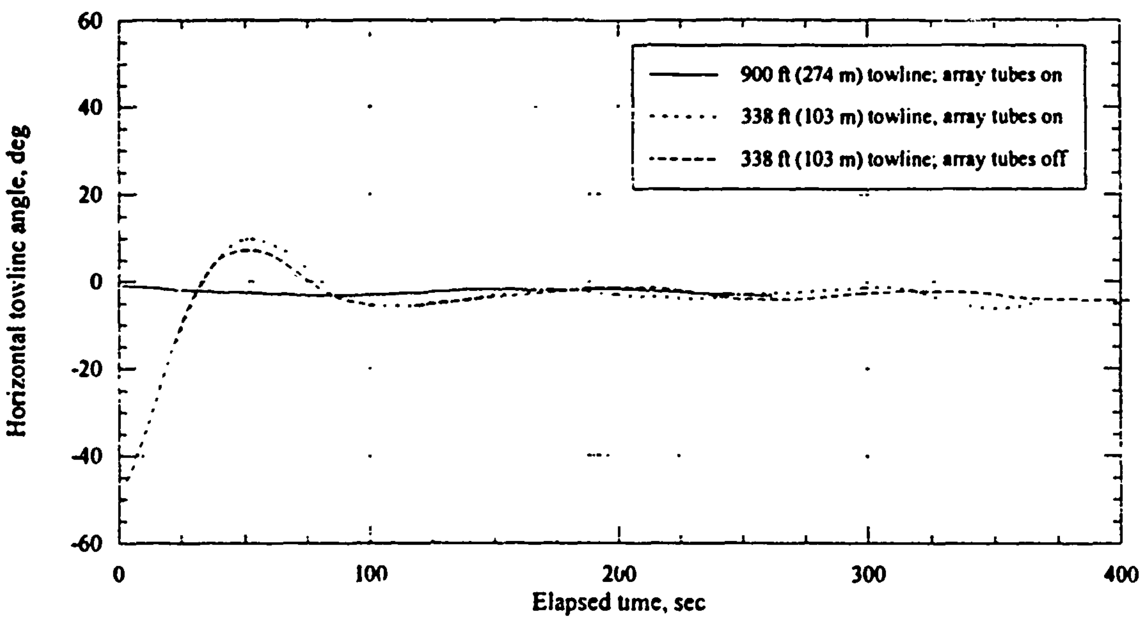

Fig 19 Effect of towline length on SSN-688 class at 5650 LTSW displacement, 0 75 ft (0.23 m) GM, 7 5 ft (2.29 m) trim down by the stern, and with an extended lower rudder and rudder plate at 7 kn.

Table 16. Horizontal towline angles for SSN–688 class submarine with a displacement of 5650 LTSW, a trim of 7.50 ft (2.29 m) down by the stern, and a GM of 0.75 ft (0.23 m) with several rudder settings.

Speed kn (m/s)	Horizontal Towline Angle, deg Extended Rudder with 1/2 Area Rudder Plate Sternplanes at 25 deg TEU Rudder Deflection, deg				
	2° P	1° P	0°	1° S	2° S
4 (2.06)	11° P		2.5° P steady	2.0° S	8.5° S wandering ± 2°
7 (3.60)	11° P		1.5° P steady	5.7° S wandering ± 2°	9.3° S wandering ± 1°
10 (5.14)					

P – Port S – Starboard

minor wandering. Horizontal towline angles as a function of time for the rudder deflection runs at 4 and 7 kn are presented in Figs. 20 and 21, respectively.

The scaled full-scale towline tension measurements for the SSN-688 class submarine with various stern appendage modifications are presented as a function of speed in Tables 17 through 22 for the 5000 LTSW displacement and Tables 23 through 30 for the 5650 LTSW displacement. Again, no data were collected at the 1.10 ft (0.34 m) GM if the 0.75 ft (0.23 m) GM configuration was found to be unstable. The full-scale towline tension estimates presented are for calm water towing. Actual at-sea average towline tension will probably be higher than measured calm water values. Towline tension peaks when towing in a sea state can be more than three times higher than the average steady state values, depending on the sea state, towline configuration, towline deployed length, tug heading, and random factors[4].

In the baseline configuration at a trim between 6.0 and 7.5 ft (1.83 and 2.29 m) down by the stern, the average steady state towline tension for SSN-688 was approximately 5600, 18000 and 36400 lb (24900, 80100 and 161900 kN) at a 5000 LTSW displacement and 5700, 18800 and 42300 lb (25400, 83600 and 188200 kN) at a 5650 LTSW displacement at speeds of 4, 7 and 10 kn, respectively.

Adding tip plates to the fixed sternplanes of SSN-688 at a 7.5 ft (2.29 m) trim down by the stern had almost no effect on the baseline tension values at either displacement.

With the rudder plate installed on the original lower rudder of SSN-688, towline tension was 15 to 20 percent higher than the baseline configuration at a trim of 7.5 ft (2.29 m) down by the stern, at either displacement, and at a speed of 10 kn.

The extended lower rudder with rudder plate modification increased the baseline tension by 20 to 24 percent at a speed of 10 kn. Increasing the trim from 6.0 to 7.5 ft (1.83 and 2.29 m) down by the stern had only a minor effect on average towline tension at either displacement.

The changes in average steady state towing tension between the Primary and Secondary towpoints were within the accuracy of the measurement in all cases. No difference in towline tension was measurable upon removal of the towed array

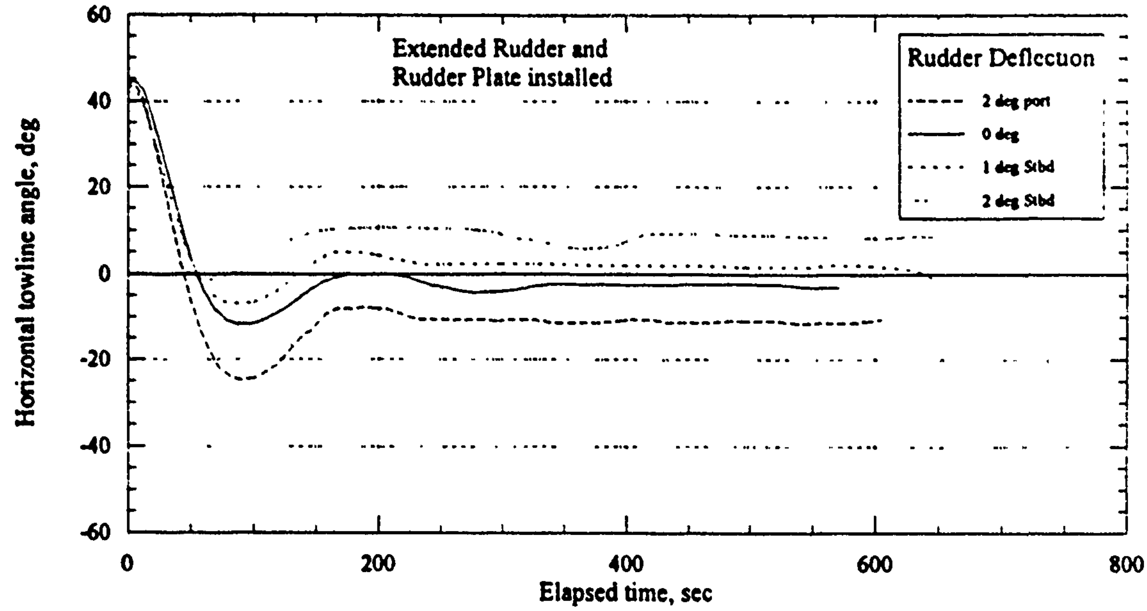

Fig. 20. Effect of rudder deflection on SSN-688 class at 5650 LTSW displacement, 0.75 ft (0.23 m) GM and 7.5 ft (2.29 m) trim down by the stern at 4 kn.

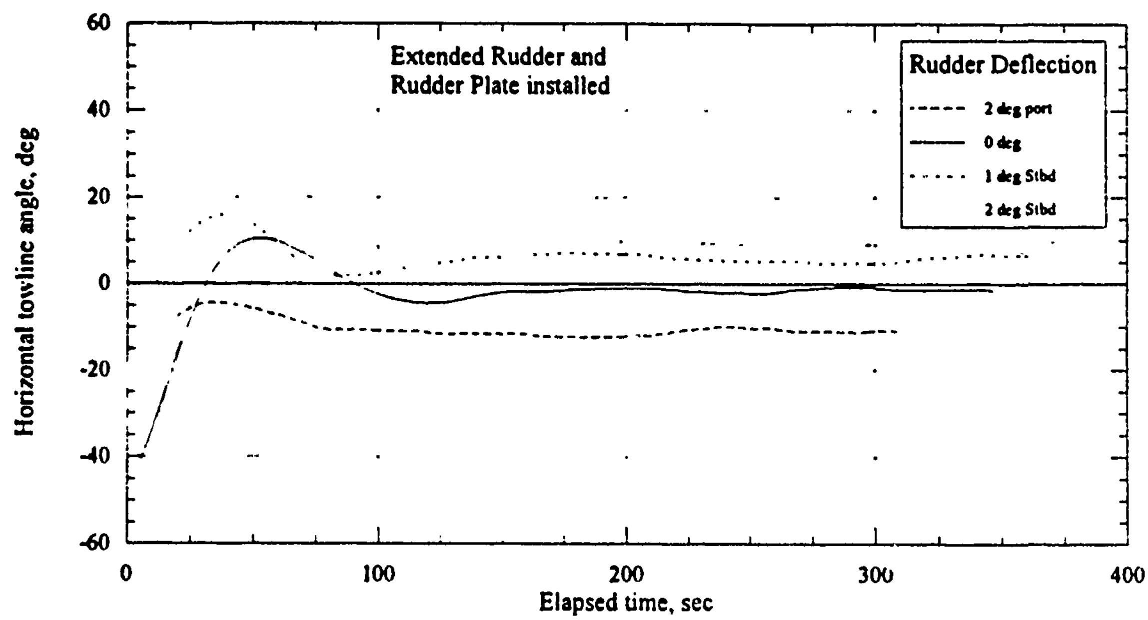

Fig. 21. Effect of rudder deflection on SSN-688 class at 5650 LTSW displacement, 0.75 ft (0.23 m) GM, and 7.5 ft (2.29 m) trim down by the stern at 7 kn

Table 17. Full-scale towline tension for SSN-688 class submarine with a displacement of 5000 LTSW, a trim of 4.50 ft (1.37 m) down by the stern, and a GM of 0.75 ft (0.23 m).

Speed kn (m/s)	Full-scale Towline Tension, lb (N)				
	Stern Configuration with Sternplane Angle, deg				
	No Extensions 25 TEU	Tip Plates 25 TEU	Aft Extensions 25 TEU	1/2 Area Rudder Plate 25 TEU	Ext. Rudder & 1/2 Area Rudder Plate 25 TEU
4 (2.06)	6,100 (27,100)				7,000 (31,100)
7 (3.60)	22,400 (99,600)				21,800 (97,000)
10 (5.14)					

Table 18. Full-scale towline tension for SSN-688 class submarine with a displacement of 5000 LTSW, a trim of 4.50 ft (1.37 m) down by the stern, and a GM of 1.1 ft (0.34 m).

Speed kn (m/s)	Full-scale Towline Tension, lb (N)				
	Stern Configuration with Sternplane Angle, deg				
	No Extensions 25 TEU	Tip Plates 25 TEU	Aft Extensions 25 TEU	1/2 Area Rudder Plate 25 TEU	Ext. Rudder & 1/2 Area Rudder Plate 25 TEU
4 (2.06)					
7 (3.60)	NO DATA COLLECTED FOR THIS CONFIGURATION				
10 (5.14)					

P – Port S – Starboard

Table 19. Full-scale towline tension for SSN-688 class submarine with a displacement of 5000 LTSW, a trim of 6.00 ft (1.83 m) down by the stern, and a GM of 0.75 ft (0.23 m).

	Full-scale Towline Tension, lb (N)				
	Stern Configuration with Sternplane Angle, deg				
Speed kn (m/s)	No Extensions 25 TEU	Tip Plates 25 TEU	Aft Extensions 25 TEU	1/2 Area Rudder Plate 25 TEU	Ext. Rudder & 1/2 Area Rudder Plate 25 TEU
4 (2.06)	6,000 (26,700)	6,100 (27,100)	6,200 (27,600)	6,200 (27,600)	6,600 (29,400)
7 (3.60)	18,900 (84,100)	17,000 (75,600)	18,500 (82,300)	18,900 (84,100)	20,200 (89,900)
10 (5.14)	36,300 (161,500)			43,500 (193,500)	46,000 (204,600)

Table 20. Full-scale towline tension for SSN-688 class submarine with a displacement of 5000 LTSW, a trim of 6.00 ft (1.83 m) down by the stern, and a GM of 1.1 ft (0.34 m).

	Full-scale Towline Tension, lb (N)				
	Stern Configuration with Sternplane Angle, deg				
Speed kn (m/s)	No Extensions 25 TEU	Tip Plates 25 TEU	Aft Extensions 25 TEU	1/2 Area Rudder Plate 25 TEU	Ext. Rudder & 1/2 Area Rudder Plate 25 TEU
4 (2.06)				6,300 (28,000)	6,100 (27,100)
7 (3.60)				20,400 (90,700)	20,700 (92,100)
10 (5.14)				45,500 (202,400)	45,100 (200,600)

Table 21. Full-scale towline tension for SSN-688 class submarine with a displacement of 5000 LTSW, a trim of 7.50 ft (2.29 m) down by the stern, and a GM of 0.75 ft (0.23 m).

Speed kn (m/s)	Full-scale Towline Tension, lb (N)				
	Stern Configuration with Sternplane Angle, deg				
	No Extensions 25 TEU	Tip Plates 25 TEU	Aft Extensions 25 TEU	1/2 Area Rudder Plate 25 TEU	Ext. Rudder & 1/2 Area Rudder Plate 25 TEU
4 (2.06)	5,200 (23,100)	4,800 (21,400)		5,400 (24,000)	6,300 (28,000)
7 (3.60)	17,200 (76,500)	18,000 (80,100)		19,900 (88,500)	20,500 (91,200)
10 (5.14)	36,600 (162,800)	36,000 (160,100)		42,700 (189,900)	45,300 (201,500)

Table 22. Full-scale towline tension for SSN-688 class submarine with a displacement of 5000 LTSW, a trim of 7.5 ft (2.29 m) down by the stern, and a GM of 1.1 ft (0.34 m).

Speed kn (m/s)	Full-scale Towline Tension, lb (N)				
	Stern Configuration with Sternplane Angle, deg				
	No Extensions 25 TEU	Tip Plates 25 TEU	Aft Extensions 25 TEU	1/2 Area Rudder Plate 25 TEU	Ext. Rudder & 1/2 Area Rudder Plate 25 TEU
4 (2.06)		5,200 (23,100)		5,600 (24,900)	6,000 (26,700)
7 (3.60)		15,900 (70,700)		20,800 (92,500)	20,500 (91,200)
10 (5.14)		36,900 (164,100)		43,900 (195,300)	45,300 (201,500)

Table 23. Full-scale towline tension for SSN-688 class submarine with a displacement of 5650 LTSW, a trim of 3.00 ft (0.91 m) down by the stern, and a GM of 0.75 ft (0.23 m).

Speed kn (m/s)	Full-scale Towline Tension, lb (N)				
	Stern Configuration with Sternplane Angle, deg				
	No Extensions 25 TEU	Tip Plates 25 TEU	Aft Extensions 25 TEU	1/2 Area Rudder Plate 25 TEU	Ext. Rudder & 1/2 Area Rudder Plate 25 TEU
4 (2.06)	7,500 (33,400)				8,200 (36,500)
7 (3.60)	24,300 (108,100)				23,300 (103,600)
10 (5.14)	44,100 (196,200)				53,200 (236,600)

Table 24. Full-scale towline tension for SSN-688 class submarine with a displacement of 5650 LTSW, a trim of 3.00 ft (0.91 m) down by the stern, and a GM of 1.1 ft (0.34 m).

Speed kn (m/s)	Full-scale Towline Tension, lb (N)				
	Stern Configuration with Sternplane Angle, deg				
	No Extensions 25 TEU	Tip Plates 25 TEU	Aft Extensions 25 TEU	1/2 Area Rudder Plate 25 TEU	Ext. Rudder & 1/2 Area Rudder Plate 25 TEU
4 (2.06)					
7 (3.60)	NO DATA COLLECTED FOR THIS CONFIGURATION				
10 (5.14)					

Table 25. Full–scale towline tension for SSN–688 class submarine with a displacement of 5650 LTSW, a trim of 4.50 ft (1.37 m) down by the stern, and a GM of 0.75 ft (0.23 m).

	Full–scale Towline Tension, lb (N)				
	Stern Configuration with Sternplane Angle, deg				
Speed kn (m/s)	No Extensions 25 TEU	Tip Plates 25 TEU	Aft Extensions 25 TEU	1/2 Area Rudder Plate 25 TEU	Ext. Rudder & 1/2 Area Rudder Plate 25 TEU
4 (2.06)	5,500 (24,500)				7,700 (34,300)
7 (3.60)	18,000 (80,100)				22,500 (100,100)
10 (5.14)	42,200 (187,700)				51,400 (228,600)

Table 26. Full–scale towline tension for SSN–688 class submarine with a displacement of 5650 LTSW, a trim of 4.50 ft (1.37 m) down by the stern, and a GM of 1.1 ft (0.34 m).

	Full–scale Towline Tension, lb (N)				
	Stern Configuration with Sternplane Angle, deg				
Speed kn (m/s)	No Extensions 25 TEU	Tip Plates 25 TEU	Aft Extensions 25 TEU	1/2 Area Rudder Plate 25 TEU	Ext. Rudder & 1/2 Area Rudder Plate 25 TEU
4 (2.06)					
7 (3.60)	NO DATA COLLECTED FOR THIS CONFIGURATION				
10 (5.14)					

Table 27. Full–scale towline tension for SSN–688 class submarine with a displacement of 5650 LTSW, a trim of 6.00 ft (1.83 m) down by the stern, and a GM of 0.75 ft (0.23 m).

Speed kn (m/s)	Full–scale Towline Tension, lb (N)				
	Stern Configuration with Sternplane Angle, deg				
	No Extensions 25 TEU	Tip Plates 25 TEU	Aft Extensions 25 TEU	1/2 Area Rudder Plate 25 TEU	Ext. Rudder & 1/2 Area Rudder Plate 25 TEU
4 (2.06)	5,200 (23,100)			6,100 (27,100)	7,100 (31,600)
7 (3.60)	17,900 (79,600)			20,600 (91,600)	23,100 (102,800)
10 (5.14)	42,300 (188,200)			49,700 (221,100)	51,100 (227,300)

Table 28. Full–scale towline tension for SSN–688 class submarine with a displacement of 5650 LTSW, a trim of 6.00 ft (1.83 m) down by the stern, and a GM of 1.1 ft (0.34 m).

Speed kn (m/s)	Full–scale Towline Tension, lb (N)				
	Stern Configuration with Sternplane Angle, deg				
	No Extensions 25 TEU	Tip Plates 25 TEU	Aft Extensions 25 TEU	1/2 Area Rudder Plate 25 TEU	Ext. Rudder & 1/2 Area Rudder Plate 25 TEU
4 (2.06)				6,300 (28,000)	7,000 (31,100)
7 (3.60)				21,600 (96,100)	22,300 (99,200)
10 (5.14)				49,200 (218,900)	51,200 (227,700)

Table 29. Full-scale towline tension for SSN-688 class submarine with a displacement of 5650 LTSW, a trim of 7.50 ft (2.29 m) down by the stern, and a GM of 0.75 ft (0.23 m).

Speed kn (m/s)	Full-scale Towline Tension, lb (N)				
	Stern Configuration with Sternplane Angle, deg				
	No Extensions 25 TEU	Tip Plates 25 TEU	Aft Extensions 25 TEU	1/2 Area Rudder Plate 25 TEU	Ext. Rudder & 1/2 Area Rudder Plate 25 TEU
4 (2.06)	6,100 (27,100)	6,400 (28,500)		6,000 (26,700)	6,200 (27,600)
7 (3.60)	19,700 (87,600)	19,000 (84,500)		21,400 (95,200)	22,000 (97,900)
10 (5.14)	42,300 (188,200)	43,200 (192,200)		48,000 (213,500)	50,600 (225,100)

Table 30. Full-scale towline tension for SSN-688 class submarine with a displacement of 5650 LTSW, a trim of 7.5 ft (2.29 m) down by the stern, and a GM of 1.1 ft (0.34 m).

Speed kn (m/s)	Full-scale Towline Tension, lb (N)				
	Stern Configuration with Sternplane Angle, deg				
	No Extensions 25 TEU	Tip Plates 25 TEU	Aft Extensions 25 TEU	1/2 Area Rudder Plate 25 TEU	Ext. Rudder & 1/2 Area Rudder Plate 25 TEU
4 (2.06)		6,000 (26,700)		5,700 (25,400)	6,000 (26,700)
7 (3.60)		18,900 (84,100)		20,700 (92,100)	21,900 (97,400)
10 (5.14)		43,000 (191,300)		48,500 (215,700)	49,300 (219,300)

tubes/fairings.

A video documentary of the SSN-688 class towing stability evaluation was prepared for distribution with this report. The video shows the David Taylor Model Basin facility, model refurbishment in the woodshop, model ballasting in the dry dock, measurement systems on the towing carriage and two towing runs comparing a model configuration with and without a rudder plate.

CONCLUSIONS

The following conclusions are made based on the results of this evaluation:

1. In the baseline configuration, with no modified or added stern appendages and with the moveable sternplanes set to 25 deg trailing edge up (TEU), the SSN-688 class was unstable at a displacement between 5000 and 5650 LTSW at a trim between 3.0 and 7.5 ft (0.91 and 2.29 m) down by the stern. In most cases, horizontal towline angles were larger than 20 deg. Smaller horizontal towline angles were observed at the 5650 LTSW displacement with a large trim to the stern but the submarine was considered positionally unstable due to excessive random wandering. Note that all trims indicated are measured between forward and aft draft marks as shown in Fig. 5.

2. A configuration with aft extensions attached to the moveable sternplanes at an angle of 25 deg TEU was only evaluated for one ballast condition. The aft extension configuration provided negligible additional stability over the baseline configuration and was not evaluated further.

3. The addition of tip plates to the fixed sternplanes (with the towed array tubes removed) and with the moveable sternplanes at an angle of 25 deg TEU was effective in stabilizing the SSN-688 class to horizontal towline angles of less than 15 deg only at a trim of 7.5 ft (2.29 m) down by the stern. At the 7.5 ft (2.29 m) trim with tip plates attached, the SSN-688 tended to wander randomly more frequently and to larger horizontal towline angles than with other modifications attached.

4. With a 1/2 Area Rudder Plate installed on the original lower rudder and with the moveable sternplanes at 25 deg TEU, a stable tow was achieved for the SSN-688 class at a trim of 7.5 ft (2.29 m) down by the stern at a displacement between 5000 and 5650 LTSW and a GM between 0.75 and 1.10 ft (0.23 and 0.34 m). Some wandering was observed at tow speeds approaching 10 kn, however the towline angles were less than 10 deg for all but one condition.

5. The most stable tow was achieved with the lower rudder extended 2.25 ft (0.69 m) with flat plate, with a 1/2 area Rudder Plate installed in a lower position on the rudder, and with the moveable sternplanes at 25 deg TEU. In this configuration, a stable tow was achieved for the SSN-688 class at a trim between 6.0 and 7.5 ft (1.83 and 2.29 m) down by the stern at a displacement between 5000 and 5650 LTSW and a GM between 0.75 and 1.10 ft (0.23 and 0.34 m) for tow speeds up to 10 kn. Occasional wandering of 1 or 2 deg was observed but horizontal towline angles were 6 deg or less for all conditions.

6. Moving the towpoint location from the Primary position (on the centerline 2 ft forward of the forward perpendicular) to the Secondary position (2 ft above the Primary position) did not have a significant effect on average steady state horizontal towline angle or towing tension at speeds up to 10 kn.

7. The SSN-688 class submarine was evaluated with the sternplane towed array tubes either attached or removed for several stable towing configurations. No significant change to either horizontal towline angle or towline tension was measured at speeds up to 10 kn.

8. With the extended rudder and rudder plate attached, the lower rudder was intentionally set to deflections of 1 and 2 deg port and starboard. The resulting horizontal towline angle measurements indicate that a small rudder deflection can increase the towline angle by 10 deg at tow speeds of 4 and 7 kn and can initiate minor wandering.

9. In the baseline configuration at a 5000 LTSW displacement and at a trim between 6.0 and 7.5 ft (1.83 and 2.29 m) down by the stern, average steady state towline tension was approximately 5600, 18000 and 36400 lb (24900, 80100, and 161900 N) at 4, 7 and 10 kn, respectively. In the baseline configuration at a 5650 LTSW displacement and at a trim between 6.0 and 7.5 ft (1.83 and 2.29 m) down by the stern, average steady state towline tension was approximately 5700, 18800 and 42300 lb (25400, 83600, and 188200 N) at 4, 7 and 10 kn, respectively. Average steady state towline tension was approximately 10 to 15 percent higher than the baseline configuration with a rudder plate on the original lower rudder. Average towline tension was approximately 2 to 5 percent higher when the rudder plate was lowered on the extended rudder at the same ballast condition at 7 and 10 kn. When the displacement was increased from 5000 to 5650 LTSW with either rudder plate attached, average towline tension was approximately 7 and 10 percent higher at 7 and 10 kn, respectively. Increasing the trim from 6.0 to 7.5 ft (1.83 to 2.29 m) down by the stern, had only a minor effect on average towline tension with either rudder plate attached.

RECOMMENDATIONS

1. To produce the most stable towing configuration for the SSN-688 class, the lower rudder should be extended 2.25 ft (0.69 m) lower with flat plate and a rudder plate 10.1 ft (3.08 m) wide and 11.8 ft (3.60 m) long should be attached to the lower rudder at an angle of 25 deg trailing edge up. The plate area on each side of the rudder should be approximately equal to 50 percent of the area of one moveable sternplane. The moveable sternplanes should be set to an angle of 25 deg trailing edge up. With these modifications, the SSN-688 class can be towed in a stable manner with a displacement between 5000 and 5650 LTSW, a trim between 6.0 ft (1.83 m) and 7.5 ft (2.29 m) down by the stern and a metacentric height (GM) between 0.75 ft (0.23 m) and 1.1 ft (0.34 m) using either the Primary or Secondary towpoint described above.

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